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THE CCV CONCEPT AND SPECIFICATIONS

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16. Abstract As defined at present, the CCV concept consists in taking into account, at the design stage of a new aircraft, the possibilities offered by four systems: static stability compensation, manuever load control, active ride control and active flutter control. Actually, the CCV concept should be understood in a much wider context; this philosophy could be summed up as follows: to take advantage of the latest technical advances in electronics (e.g. reliability and miniaturization) and to make use of new types of control surfaces to make the optimum compromise between performance, handling qualities, lifetime and cost. One of the results of this philosophy is the abandonment of the aircraft "natural" stability requirements (static stability and structural stability, i.e., absence of flutter in the flight range). The discussion thus attempts to answer the question of whether new specifications for aircrafts designed along the CCV concept should be written.

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THE CCV CONCEPT AND SPECIFICATIONS

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The CCV concept and its French equivalent, systems integration, which has been under development for several years, will soon leave the realm of theory and research for actual use in the design of combat aircraft of the next generation and, at least in part, that of future transport aircraft. /22-1*

So far used only in purely experimental aircraft, CCV systems have not been subjected to safety regulations other than those usually applied to this type of aircraft, in which the risks of breakdown or mechanical failure are compensated for by specific use and maintenance regulations (trained test pilots, radio listening-in by specialists, accurate meteorological reports, guidance possible on emergency landing fields, possibility of halting local air traffic, permanent recording of various operating parameters and checking of systems between flights, etc.).

When these systems are used in combat or transport aircraft, however, they will have to meet precise regulations insuring that the safety level which may be expected of aircraft of this generation is not lowered. This brings up the problem of the type of regulations which should be applied to aircraft built on the CCV principle. Should MIL SPEC 8785 B and 83300, AGARD 577, AvP 970, FAR 25 and TSS 3 be changed to take these new systems into account? This is the question which we will try to answer here, after outlining the basic principles of the CCV concept.

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* Numbers in the margin indicate pagination in the foreign text.

Quite frequently, the CCV concept is presented as the use of four main systems which eliminate a given number of limitations in designing a new aircraft. These four systems are:

a) aircraft static stability compensation;
b) active ride control;
c) maneuver load control;
d) active flutter control.

The static stability compensation system permits partial freedom from the problem of balance during the design process and makes it possible to decrease the size of the tail unit and trim drag. /22-2

Both active ride control and maneuver load control allow a decrease in the weight of the structure.

Finally, active flutter control reduces structural fatigue and improves the comfort of the crew.

The use of these four systems in a bomber or transport airplane results in considerable gains in regard to takeoff weight, and thus installed power (gain in weight of structure, gain in drag and thus in fuel weight). On the other hand, application of the CCV concept to fighter aircraft results in the use of systems which, whether they are similar or different, will produce gains for different reasons.

For this reason, the addition of direct lift and lateral force control surfaces increases the combat maneuverability of the aircraft and makes its attitude partially independent of trajectory (improvement in firing platform). Static stability compensation permits a reduction of the stabilizer surface areas and a reduction in trim drag during maneuvering, which increases the maximum balanced load factor. In conjunction with this system, active flutter control makes it possible to design a clean configuration without concern for the problem of external loads. (The addition of external loads generally moves the balance to the rear, brings the focal point forward and reduces the critical flutter speed.)

To regress slightly, in the final analysis the basic philosophy of the CCV concept appears to be the following: "To attain a maximum reduction in takeoff weight and installed power, that is, to decrease the cost of the project while at the same time obtaining given performances, by omitting a few customary or preconceived notions whose cost is generally high."

In other words, designing an aircraft on this principle consists in:

-- not making a priori use of the natural stability (stability around the center of gravity, structural stability, that is, lack of flutter within the flight range);

-- to design new control surfaces to meet new needs (flutter control, direct lift, lateral force, maneuver load distribution, etc.) or control surfaces whose latent defects may be compensated for by the static stability compensation system (canard, for example);

-- to make use of electrical control channels and new pilot controls (micromanipulator);

-- to offer the pilot new data.

This list might even include multiplexing of data, that is, data transmission by omnibus bars in place of specialized circuits.

We might now consider in what areas safety problems are going to arise.

The first and most obvious consideration is the problem of reliability of the systems. The second is that of handling qualities, which are influenced by the use of new control surfaces, new pilot controls and new data presentation systems.

Let us first examine the problem of systems reliability.

In regard to the electrical control channels, the situation today is similar to that of twenty years ago, when the possibility of no longer connecting the control column and rudder pedals to the control surfaces and instead relying solely on hydraulic transmission was first being considered. Nevertheless, it should be recognized that the current situation is much more favorable, since the bases for reliability research are much more solid than formerly. In addition, the regulations, which have already been changed to allow for simple hydraulic transmission, could easily be adapted to electrical transmission. There would be no need to change TSS 3 and MIL SPEC 8785 B and 83300, which are based on the same fundamental principles, with no a priori assumptions on systems reliability. On the other hand, methods for demonstration of compliance with the regulations should be developed so as to obtain a satisfactory demonstration of the reliability of the system. It might be pointed out once again that an answer to this question could not be supplied by an overall demonstration of real flight characteristics. The actual problem is to demonstrate probabilities of failure on the order of 10^{-6} to 10^{-7} per hour of flight. Now, to demonstrate a probability of failure of less than 10^{-n} per hour with a confidence level of 0.9 will require operation for $2.3 \cdot 10^{n}$ hours without failure, $3.9 \cdot 10^{n}$ hours with only one failure, $5.3 \cdot 10^{n}$ hours with only two failures, etc. Thus a direct demonstration of 10^{-6} or 10^{-7} is strictly impossible. Only probabilities on the order of 10^{-2} to 10^{-3} per hour may be attained experimentally. As a result, the reliability of a complete system can be estimated only by calculations based on the redundancy of elements whose probability of failure has been shown experimentally to be on the order of 10^{-3}. One must still watch out if the redundancy of the systems maintains the independence of the elements: can two elements from the same production series subjected to the same conditions really be considered independent? Experience has shown that this is definitely not the case, and that the probability of simultaneous failure of two elements is much greater than the square of the probability of simple failure (simultaneous failure being taken as the failure of two elements during the same flight). Remarkable advances in electronic miniaturization allow for the use of a much larger number of channels, circuits and systems than that currently conceivable with available mechanical and hydraulic systems. A solution, however, may not be in a redundancy of numerous identical systems, but rather in the use of several parallel systems performing the same function (with some systems performing the same function, but simplified), designed on the basis of different principles, configurations and techological methods and installed in different parts of the aircraft. The purpose of this method is to make the systems truly independent, and in addition, to decrease the vulnerability of combat aircraft.

It has just been noted that a demonstration of reliability cannot be obtained directly by flight tests of prototypes or pre- /22-3 production aircraft. Nevertheless we should not assume from this that flight tests are useless. It is impossible to conclude that the reliability of the systems is adequate merely on the basis of 1000 or 2000 hours of flight testing without failure; on the other hand, this is the only method of checking the operation of each of the systems under real conditions and evaluating the probability of failure. However, only theoretical analysis of the way in which the elementary systems make up the complete system permits conclusions as to the reliability of the whole, on the basis of elementary failure probability estimates obtained at the test bench and confirmed by flight tests.

Of course, there was no need to wait for the arrival of the CCV concept to research and develop these methods of reliability analysis. As a specific example, the certification of the Concorde was based in large part on these methods; it might be recalled, for example, that the balance of the Concorde in supersonic flight was such as to make the aircraft unstable in subsonic flight. Obviously, to have an aircraft whose inflight balance is such that approach and landing are impossible, one must demonstrate that the probability of failure of the fuel transfer system is reasonably slight. (The probability of a single failure preventing the return to subsonic balance over the life of all aircraft in service should be sufficiently low for this occurrence to be considered improbable.)

Nevertheless it is still necessary to improve methods of analysis on a number of points: systematic determination of critical cases, reduction of calculation time, estimating of elementary probabilities (calculation, simulation testing, flight testing), etc., all these procedures being designed to construct more reliable and accurate methods of demonstration in conformity with regulations.

Before moving on to the problems of handling qualities, one final observation should be made in regard to the level of probability of failure which should be required of the various systems in order to obtain an acceptable overall safety level for civil and military aircraft and a reasonable probability of mission success for military aircraft.

Let us first examine the case of military aircraft.

Currently it is an accepted possibility that a few aircraft in a fleet may be lost due to failures preventing continuance of the mission (failure of the jet engine in a single-engine airplane, total failure of the hydraulic circuit of the servo control system, etc.), to the extent, however that methods are available allowing the pilot a reasonable chance of not being killed in the crash. (Thus the pilots of some single-engine figher aircraft are instructed to eject in case of engine failure.)

Choice of the reliability level of the CCV system may thus be made in the following manner.

A "basic" CCV system, that is, one with the minimal circuits for obtaining CCV functions, makes it possible, at given performances, to decrease the weight of the structure and the amount of fuel necessary for a mission. The result is an overall benefit of x% in the purchase price and utilization costs of each airplane. (By utilization cost, we mean the expenditures necessary for the operation of each airplane throughout the period of utilization of this type of aircraft.) If we improve the reliability of the CCV system by increasing the redundancy of various circuits, it is obvious that we will increase the purchase price of each aircraft as well as its utilization cost (increase in hours of systems maintenance). Thus the advantage over conventional aircraft decreases as the reliability of the systems increases.[1]

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[1] In drawing up a balance sheet one must take care not to forget the improvements in the ejection system which may turn out to be necessary (zero-zero seat, for example, which is not indispensable in a conventional multi-engine airplane).

In addition, any probability p (per hour) of failure in the CCV system resulting in loss of the airplane has corresponding probabilities Q_k of there being losses of aircraft between zero and k for a fleet of N airplanes each performing n hours of flight. Assuming $Q_k = 0.99$, one obtains a satisfactory estimate of the number k of losses per failure in CCV system which might reasonably be expected throughout the utilization period of the fleet. (The chance of there being a real number of accidents greater than k is only 1 in 100.)

If p is the probability of failure per hour, the probability of there being no accidents during n hours of flight of the aircraft is $p_1 = (1 - p)^n$, and the probability of accident is $p_2 = 1 - p_1$. Thus the probability Q_k of accidents between 0 and k for the N aircraft in the fleet is:

$$Q_k = \sum_{m=0}^{m=k} \binom{m}{n} p_1^{n-m} p_2^{m} \tag{1}$$

When the product Np_2 is high enough, a satisfactory approximation of the number k corresponding to a given value of Q_k is given by:

$$k = \lambda \sqrt{np_1 p_2} + np_2 \tag{2}$$

λ being determined by

$$Q_k = \int_{-\infty}^{\lambda} \frac{e^{-\frac{x^2}{2}}}{\sqrt{2\pi}} dx \quad \text{(normal law)}$$

for $Q_k = 0.99$, $\lambda = 2.3264$, and for $Q_k = 0.5$, $\lambda = 0$.

To determine the orders of magnitude, let us examine the law k(p) corresponding to $Q_k = 0.99$ for a fleet of 1000 airplanes intended to perform 5000 hours of flight each. (The computations have been performed with equation (1) for $p < 10^{-6}$.)

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$Q_k = 0.99$									
p	10^{-4}	$5 \cdot 10^{-5}$	10^{-5}	$5 \cdot 10^{-6}$	10^{-6}	$5 \cdot 10^{-7}$	10^{-7}	$5 \cdot 10^{-8}$	10^{-8}
k	430	252	65	37	11	7	3	2	1

To determine the influence of Q_k on this result, let us also gives the laws k(p) for $Q_k = 0.5$ (one chance in two of having more than k losses) and $Q_k = 0.999$ (one chance in 1000 of having more than k losses) (for $Q_k = 0.999$; $\lambda = 3.0902$).

$Q_k = 0.5$									
p	10^{-4}	$5 \cdot 10^{-5}$	10^{-5}	$5 \cdot 10^{-6}$	10^{-6}	$5 \cdot 10^{-7}$	10^{-7}	$5 \cdot 10^{-8}$	10^{-8}
k	394	222	49	25	5	2	0	0	0

$Q_k = 0.999$									
p	10^{-4}	$5 \cdot 10^{-5}$	10^{-5}	$5 \cdot 10^{-6}$	10^{-6}	$5 \cdot 10^{-7}$	10^{-7}	$5 \cdot 10^{-8}$	10^{-8}
k	442	262	70	40	13	9	4	3	2

It can be seen from these figures that the reliability factor for the CCV system is reasonably close to 10^{-6}: the 1% loss is acceptable to the crews from a psychological standpoint, since the probability of loss of the crew itself is much lower (resulting in the problem of the reliability of the ejection system); this factor, of course, is valid only if the overall benefit x due to the CCV system is higher than 1%.

It should be recognized that in order to attain a probability of failure of 10^{-6} per hour, it is necessary to triple the system[2]. (It has been seen earlier that the highest experimental probability which may be expected for the elementary systems is on the order of 10^{-3}; to demonstrate that p is less than 10^{-6}, there must therefore be two independent systems.)

Thus it is by no means evident that the cost of a CCV system designed in this way will result in an overall gain of more than 1%.

The problem is slightly different with civilian aircraft, since here one must ensure the safety of paying passengers who will not be able to evacuate the aircraft in case of a total failure of the system. In addition, civilian aircraft is designed to perform a much higher number of flying hours than military aircraft: on the order of 30,000 rather than 5000.

Currently, the overall reliability factor imposed by civilian regulations is on the order of 10^{-7} per hour. (With aircraft of the generation now being used by commercial air lines, the probability of failure resulting in a crash is more on the order of 10^{-6} per hour.) Let us see how many crashes this will result in for a fleet of 1000 airplanes.

For $n = 30{,}000$ hours, $N = 1000$ and $p = 10^{-6}$, one obtains:

for $Q_k = 0.5$	$k = 30$
$Q_k = 0.99$	$k = 42$
$Q_k = 0.999$	$k = 50$

[2] The hydraulic circuits are generally only doubled, but it should be recognized that designers have accumulated a considerable amount of flight experience permitting more accurate determination of the reliability of these systems and that the rules of the art insuring the constancy of this reliability level are now solidly established.

For $n = 30{,}000$ hours, $N = 1000$ and $p = 10^{-7}$, one obtains

for $Q_k = 0.5$ $\quad k = 3$

$Q_k = 0.99$ $\quad k = 7$

$Q_k = 0.999$ $\quad k = 9$

It may be seen that the 10^{-7} factor again represents an expected loss of seven aircraft out of 1000 in service. At present, however, it is difficult to require reliability for CCV systems resulting in an elementary probability of less than 10^{-7}, since there is no reason to require more of this system than conventional systems. At the very most it is our intention to show that the 10^{-7} factor, which is reasonable for the coming decade from a reliability standpoint, is only a single step in safety research. (Moreover, in its initial stage the increase in safety should come more from improvements in navigation and control during takeoff, approach, and landing than from improvements in the reliability of the systems.) /22-5

We have just seen what the probability of failure resulting in a crash should be. This factor is valid for the electrical control system or the static stability compensation system, but a failure in any CCV system does not always result in a crash.

Obviously, failures in the active ride control and maneuver load control systems will not have serious consequences -- provided that they do not cause an immediate safety problem due to untimely deflection of a control surface, taking the airplane out of control -- since the sole purpose of these devices is to improve the comfort and fatigue life of the airplane. Simple systems are thus perfectly acceptable from the standpoint of safety alone. (On the other hand, considerations of comfort in use or the success of operating missions may lead to improvements in the reliability of the active ride control system.)

In regard to the active flutter control system, the temptation at first glance would be to require reliability on the same order as that of the electrical control or static stability compensation systems.

Actually, the use conditions of a system of this type must be taken into account. In a civilian transport airplane, the active flutter control system may be used to thrust the critical speed farther into the peripheral range, in other words, to permit flight with a reduced margin in comparison to the critical natural flutter speed. Under these conditions, a crash may occur only if the peripheral range beyond the natural critical speed is entered and there is a simultaneous failure in the active flutter control system during this period. The probability of crash is thus the product of the probability of exceeding the natural critical speed and the probability of failure of the system. Given the low probability of exceeding the natural critical speed and the short amount of time spent beyond this speed, the probability of failure of the system may be relatively high (on the order of 10^{-3} to 10^{-4}). This problem is very similar to that found with safety devices designed to operate in the peripheral range, such as the "stick shaker" or "stick pusher," for example.

On the other hand, the active flutter control system of a combat aircraft may be made to perform actually within the authorized range. In this case, the reliability required will depend on the consequences of the failure: if the result is the release of explosive flutter, it is obvious that the probability of failure must be on the order of that required for the electrical control or static stability compensation systems. On the other hand, if the device is designed to combat flutter due to the presence of external loads, the problem may be somewhat different; this type of flutter is generally relatively slack and may allow a safety device sufficient time to jettison the external loads. Under these conditions, here again a decreased reliability for the system may be accepted.

We now come to the second point involving safety. This is the problem of the effect of the CCV concept on requirements for handling qualities, or more precisely, on pilotability.

The general objective for any pilotability requirements is given by TSS 3: "The aircraft should have sufficiently high pilotability characteristics so that the execution of each subphase and related maneuvers is not too difficult or fatiguing for the crew, taking into account the length of the subphase and the probability of the state of the airplane and the state of the atmosphere. In other words, the combined physical and mental activities necessary for the execution of each subphase should not result in excessive fatigue for the crew, so as to limit the risk of judgmental errors or faulty maneuvers."

In regard to the controls, TSS 3 stipulates that "it should be possible to perform all manipulations of the controls in accordance with the flight manual without excessive strain on the crew. Specifically, the effort needed to manipulate the controls in the authorized manner should not be too great, given the emplacement, shape and dimensions of the controls, as well as the period for which this effort must be applied. This rule also applies to the effort needed to operate the controls following manipulation of a selector during a change in selected configuration."

These basic principles being outlined, two methods of demonstration of compliance are proposed:

-- the classical method which is found in appreciably equivalent form in all regulations (the strictness of the requirements differs depending on whether they come from military specifications or civilian airworthiness regulations; this is due to the fact that the sole objective of civilian regulations is the safety of the individuals, transported or flown over, while the objective of a military specification is not only safety, but also the effectiveness of the mission);

-- a method based on evaluation of the workload by a scale of the Cooper-Harper type.

Let us first see how the classical method may be applied to aircraft built on CCV principles.

Four types of pilotability specifications are required:

a) stability specifications;

b) specifications concerning the response of the aircraft to the controls;

c) specifications dealing with controls loads (maximum load and possibility of override);

d) specifications dealing with the effects of changes in configuration and on the general behavior of the aircraft (trajectory, attitude, control loads). /22-6

There is no problem in applying stability requirements to a CCV airplane. The only place a problem may arise is in justifying the stability requirements themselves in the case of flight phases where the speed varies relatively quickly. This case is provided for in TSS 3, but the methods of demonstration of conformity are not yet completely developed. Since this problem is not specific to CCV aircraft, it will not be dealt with here. (It is handled specifically by the Handling Quality Committee.)

Similarly, specifications concerning the effect of changes in configuration may be applied to CCV aircraft without difficulty. Moreover, it may be predicted that it will be somewhat easier to meet these requirements in the case of CCV; changes in the equilibrium positions of the control surfaces during extension of the landing gear, flap shutters, leading edges, speed brakes, etc. may be more easily modulated, taking flight conditions into account (speed, altitude, weight and balance), due to the fact that the control surfaces are electrically controlled. The only problem is the reliability of the connections.

On the other hand, research should be performed on the load laws for the micromanipulators to take into account the dimensions, shape and emplacement of the these controls, as stated above. This problem should be easy to solve by means of simulator and in-flight testing.

In the final analysis, the most difficult problems will occur in the area of the response of the aircraft to the controls -- provided, however, that the pilot has specific controls to activate non-conventional control surfaces such as lateral force or direct lift control surfaces. Of course, if the pilot has conventional roll, yaw and pitch controls (even in the form of a micromanipulator reproducing the functions of the control column and rudder pedals), the classical requirements will apply without modification, since the pilot does not need to know whether his orders are transmitted directly to the classical control surfaces or whether his activation of the controls produces the interlinked deflection of several control surfaces. Moreover, at present this is actually the case with roll controls, which are able to activate various elevons and spoilers with different interlink ratios depending on flight conditions.

It is possible, however, to conceive of two specific controls which would act on the lateral force and direct lift control.

surfaces, or more precisely, which would produce a lateral force and a lift force which would influence the trajectory without changing the angle of attack and the sideslip angle. The pilot thus abandons the micromanipulator and a transparent automatic pilot keeps the sideslip angle at zero, the wings "horizontal" and the angle of attack at the value recommended for this flight phase (approach, ground attack, etc.). This pilot operates a second micromanipulator, whose "vertical" and "lateral" movements vary the lift and lateral force, changing the trajectory. In that case, the pilot must have data on the trajectory, for example, plotting of the speed vector to infinity; this is because the pilot no longer has a conventional data return furnished by attitude variations allowing him to apportion his actions at the controls.

It is quite obvious that a control method of this type has not been provided for in the regulations, and that new specifications must be set up to evaluate the quality of the responses of the airplane to these new controls.

Two methods may be used: either these new specifications may be established on the basis of simulator and flight tests on experimental aircraft, or the TSS 3 regulations may be applied to the airplane to be certified without modification, evaluating the workload of the pilot during the phases where the new control mode is used. Since the shape, size and emplacement of the new control system, and even the nature of the new data to be furnished to the pilot, are far from being fixed at present, it would appear wiser to use the second method, since the first could be used only after a few general rules of use have been determined by experimentation on prototypes. Furthermore, it should be noted that the first method consists in determining a given number of general criteria based on experimentation using the evaluation of workloads on the Cooper-Harper scale.

In conclusion, the CCV concept presents two types of problems in regard to safety specifications:

a) demonstration of systems reliability: methods for estimating the overall probabilities of failure must be perfected;

b) establishment of new handling quality criteria for aircraft equipped with special "trajectory" controls (lateral force and direct lift).

Aside from these areas, all the classical criteria for handling qualities may be applied without modification to aircraft built along the CCV concept.